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BPX COMMITMENT TO TOTAL REMOTE MAINTENANCE*

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BPX COMMITMENT TO TOTAL REMOTE MAINTENANCE*

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Abstract

The Burning Plasma Experiment (BPX), to be located at Princeton Plasma Physics Laboratory, is the next major experimental machine in the U.S. Fusion Program. It will be fueled with deuterium-tritium (D-T) that, when burned, will generate high-energy neutrons. This will activate the various materials used in construction of the machine, which will result in high levels of gamma radiation. Any subsequent maintenance activities on the machine or in the test cell area must be performed remotely.

The initial criteria for BPX assumed that failure of a toroidal field (TF) coil or poloidal field (PF) coil was an unlikely event. Therefore, no provisions were made for remote replacement. Expected failures were limited to the plasma-facing components and the external auxiliary equipment such as heating systems and diagnostics. Recent coil failures experienced at the Tokamak Fusion Test Reactor (TFTR), the Joint European Torus (JET), JT-60, and Tore Supra caused the BPX project staff to reconsider the need for remote replacement. A study was undertaken to investigate how the project would be affected if the capability to recover from a coil failure were required. Potential effects including configuration changes to the machine and facility, project cost, and project operation were considered.

The study revealed that it is indeed feasible to design BPX for remote recovery from any coil failure. However, for this to be accomplished effectively, it is imperative to incorporate the necessary remote maintenance features of the components to be remotely replaced into the original design along with all of the other functional features. The remote maintenance capability cannot be retrofitted after the design is complete or the equipment is built. This paper discusses the impacts of the coil remote replacement study and the subsequent changes to the machine design.

Introduction

The primary mission of the BPX project is to understand the physics of plasmas in which alpha particle heating is dominant and to demonstrate the production of substantial amounts of fusion power. The use of D-T fuel will be necessary to accomplish this mission. The fusion process using this fuel will generate high-energy neutrons high levels of ionizing radiation and the need for remote maintenance.

The original project criteria required remote maintenance only of the plasma-facing components within the vacuum vessel and of the auxiliary and diagnostics systems external to the cryostat (see Fig. 1). The BPX design did not consider TF coil and PF coil failures a credible event and therefore did not require remote replacement capability. The relatively recent coil problems experienced by TFTR, JET, JT-60, and Tore Supra caused the BPX program to reconsider its past position on coil failures. In January 1990, a study was undertaken to assess the impact of making remote recovery from a TF or PF coil failure a project requirement.

Baseline Design

The BPX fusion machine is located in the center cell of the facility and is surrounded by concrete shield walls approximately 3 m thick (see Figs. 1 and 2). The machine will initially be fueled with hydrogen for a period of one to two years. Relatively few neutrons will be produced; therefore no significant material activation will occur. During this time frame, equipment failures can be corrected by conventional hands-on techniques and remote maintenance operations can be demonstrated. Once D-T operations commence, personnel entry into the center cell will no longer be possible; all repair operations must be accomplished remotely.

The basic remote handling systems concept for BPX is shown in Fig. 3. There are five manipulator-transporter systems and two remotely operated overhead crane systems. These systems, supplemented by remotely operable tooling, are the basic capability available to correct failures within the BPX tokamak and its auxiliary systems and diagnostics in the center cell.

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Figure 1: Test Cell and Hot Repair Cell Section View.

Figure 2. Burning Plasma Experiment

Figure 3: Test Cell Manipulation System

Each of the manipulator-transporter systems maintains a specific area of the machine. The overhead system located in the high-bay area is responsible for maintaining the top and sides of the machine. The system consists of an overhead bridge-trolley with a vertically telescoping boom that supports a teleoperated manipulator package.

The "cherry-picker" mounted manipulator system consists of an articulated boom that supports a teleoperated manipulator package. This system will supplement the overhead system, particularly in the lower areas of the machine.

The components inside the vacuum vessel, such as the graphite tiles, divertor plates, etc., will be maintained by a manipulator system mounted on the end of an articulated boom similar to the booms designed for TFTR and JET.

The present concept to perform maintenance tasks under the machine is to use an articulated boom similar in configuration to the boom that will be used to perform maintenance tasks in the vessel, supplemented by a small floor-mounted vehicle equipped with a manipulator package. The boom will provide a weight handling capability, while the floor-mounted system will provide sensitivity and dexterity.

Coil Replacement Study

Following the coil problems experienced by TFTR, JET, and Tore Supra, the BPX project deemed it prudent to investigate how the program would be affected if the capability to recover from any coil failure were required. Therefore, a study was initiated to answer three basic questions:

1. Can a feasible concept be developed to provide for remote recovery?
2. What would be the additional cost to the project?
3. How would the overall project schedule change to accomplish this objective?

A detailed replacement sequence was developed for what was judged the worst-case scenario, a TF coil failure. The replacement sequence consisted of 20 major steps, listed in Table 1, with each step containing as many as 15 activities. Replacement cost and schedule estimates were generated for both hands-on and remote replacement scenarios. The estimated time to replace a TF coil is ~2 years, or ~3 times as long as hands-on replacement. The development of the replacement sequence provided a consistent and thorough basis for generating the replacement duration estimates, identifying tools and fixtures, itemizing costs, ensuring that no aspect of the replacement was overlooked. It also established a method to communicate the required replacement operations. To

accomplish the remote replacement of a failed coil, various modifications of the BPX machine were necessary. Sketches of these concepts were prepared to establish the feasibility and provide a basis for the cost estimate.

This detailed sequence of operations was used as a "script" to generate a real-time graphic simulation. Three-dimensional computer modeling with the Interactive Graphics Robot Instruction Program (IGRIP) was used extensively to investigate the remote handling requirements. IGRIP was used to model work spaces around the machine and the kinematics of the manipulators, cranes, transporters, etc. This approach proved to be a very valuable design tool. From this work, a video tape was prepared and used as a means to present the sequence of operations and the needed design changes to remotely replace a TF coil.

Machine Modifications

Many component design modifications were necessary to enhance remote maintenance. In many of the cases, the concept developed would have been adopted even if the remote maintenance requirement had not been invoked. The ability to remotely maintain requires simplicity, which normally enhances performance, reliability, and maintainability.

Cryostat and cryostat penetrations: Remote maintenance tasks within the machine outer boundary require access through the cryostat. The cryostat must be modularized with remote features for assembly/disassembly. At present, there are more than 200 penetrations through the cryostat for power buses, coolant and vent lines, electrical and instrumentation leads, access port penetrations, etc. Each penetration must be provided with a single-bellows seal system designed for remote replacement.

PF ring coils: If one of the inner PF coils forming the center solenoid fails, the entire solenoid will be replaced as a single module. The outer PF coils will be replaced as individual modules. The upper four ring coils will be individually replaced in the event of failure. They must also be removed to replace a TF module. A failed ring coil under the machine or a failed outer ring coil located below the horizontal ports will be lowered and cut into pieces to permit removal. Replacement coils, located in the cell floor during the original installation of the machine, will be remotely raised and secured into position. (Consideration was given to segmenting the ring coils to enhance the replacement operation, but this was rejected since it would require several joints per coil, greatly reducing the reliability as well as substantially increasing the cost.)

TF coil modules: A modular rather than a monolithic design was required to make TF coil replacement practical. The proposed design of the TF coil system consists of six modules, each containing three coils and one-sixth of the vacuum vessel (see Fig. 4). The vacuum

Table 1. Summary of tasks for remote replacement of a TF coil.

Activity	Number of serial shifts	Crew size	
		Technicians	Supervision + engineering
Preparations	66	10	3
Remove diagnostics	54	10	3
Prepare center cell	24	10	3
Remove cryostat dome	64	10	3
Remove upper components	22	6	3
Remove solenoid	44	5	3
Remove cryostat panels	30	6	3
Relocate PF coils	128	11	3
Section vacuum vessel	60 ^a	4	1
Remove failed module	76	7	3
Position new module	101	9	3
Connect vacuum vessel sector	96 ^a	4	1
Install new module	93	9	3
Replace PF coils	134	11	3
Replace cryostat panels	33	8	3
Replace solenoid	52	5	3
Replace upper components	29	6	3
Replace cryostat dome	113	10	3
Replace diagnostics	84	10	3
Prepare for operations	38		
Total	1351		

^aIncludes some parallel tasks.

Figure 4: TF Coil Modules.

vessel sectors are bolted together and sealed with a vacuum barrier, while the modules are welded together with very thick structural welds to resist the large overturning moments developed during machine operation. Conceivably the welds, both initial construction and remote replacement, will be made using a special-purpose track welder. Permanent track mounting brackets will be attached to the modules at each joint location. Hands-on and remote welding will use the same welding heads, tractors, tracks, and control system. For remote disassembly, the weld joint will be milled by a cutting head that replaces the welding head. This modular approach has distinct manufacturing advantages over the original monolithic design since more of the fabrication can be done at the factory, thus reducing the field assembly tasks.

Vacuum vessel: The original vacuum vessel design was a welded structure interlocked into the TF coils. To remove a TF module, remotely operable vacuum vessel joints are required at each of the module interfaces. Each joint must withstand disruption loads and provide the high-integrity vacuum seal required for fusion plasmas. The present concept incorporates a bolted flange with a

double-lip seal weld. Access is provided for cutting/welding tools and remotely operable bolt tensioning and unbolting tools.

TF and PF coil bus connectors: Remote removal/replacement of TF and PF coil assemblies requires provisions for cryogenically cooled electrical jumper assemblies with high current capacity. The development of a remotely operable cryogenic connector is part of the present R&D plans. The jumper must provide sufficient compliance to engage, yet be self-supporting while being remotely handled.

Facility: Additional space must be provided for both cold and radioactively hot equipment. Significant space will be needed for storage of the equipment and tooling required to replace a failed coil and for a staging area to prepare the new equipment items. Hot storage will be required for activated components that are removed from the machine. Any area used for hot storage automatically requires remote operations until the activated materials are removed. Equipment transfer routes and repair cell space and handling systems must be re-evaluated in light of the additional requirements imposed by remote coil replacement. The role of the high-bay area must be reassessed with respect to the elimination of personnel access during a prolonged shutdown for a TF coil replacement.

Total remote maintainability of BPX requires design modifications to many of the major machine components as discussed within this paper. To achieve this capability in the most effective manner, the necessary remote maintenance features must be incorporated into the design of each component from the start. This will require a complete commitment by the entire project team that views remote maintenance as important as any other functional requirement.

The capability to remotely replace coils provides a broader capability to respond to other unanticipated failures. It is these unexpected events that have historically plagued remotely maintained facilities. If the project is prepared for these certain, yet unknown events, the overall project availability will be significantly improved.

Mock-Ups

The additional remote maintenance requirements to accommodate remote coil replacement demand an increase in the degree and scale of mock-ups. Preliminary design must recognize critical design features and the need for remote maintenance mock-ups to verify or reject these features. These mock-ups must continue to evolve during the refinement of the component designs and development of the tooling. Final validation tests will take place during final assembly of the machine, when key operations will be performed using remote tooling under simulated remote operational conditions.

Conclusions

The study substantiated the following:

1. Remote replacement of a failed TF coil is feasible.
2. The cost of incorporating the capability for remote replacement would be less than 6% of the total project costs.
3. Replacement of a failed TF coil would require approximately two years.

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